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Hour-scale wind fluctuations over the North Sea

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Abstract:

The predictability of hour-scale wind fluctuations at the Horns Rev I wind farm is explored from two perspectives. Firstly, observed hour-scale wind fluctuations for the four year period 2000–2003 are related to the large scale weather patterns over northwest Europe and the northeast Atlantic Ocean. It is found that there are certain weather patterns associated with an enhanced risk of severe hour-scale wind fluctuations, and that these weather patterns mostly relate to flow from the west to northerly directions with a deep northerly component.

Secondly, an observed episode of large hour-scale wind speed fluctuations is modelled using the Weather Research and Forecasting model with a horizontal grid spacing of 2 km. It is shown that realistic cellular convection patterns develop in the simulation, and that corresponding large fluctuations in the horizontal wind speed are reproduced.

The practical use of day-ahead forecasts of hour-scale wind fluctuations is discussed, and it is argued that while it is unlikely that the precise phase of individual wind fluctuations could be forecast, it is reasonable that the onset, amplitude and frequency of such events could be predicted.

Keywords: Wind fluctuations, predictability, self organising maps, mesoscale modelling

1 Introduction

Large wind fluctuations with a period of one to several hours are often observed at the Horns Rev I offshore wind farm in the North Sea. An example of this phenomenon is shown in the time series of wind speed observations from a meteorological mast near the Horns Rev wind farm between 21 and 26 February 2002 (figure 1). It is obvious that the statistical properties of the wind speed changed markedly on 22 February, and again on 25 February.

Fluctuations in wind speed lead to fluctuations in the power produced by wind turbines. For offshore wind farms, the high concentration of turbines within a small geographical area means that there is limited potential for the smoothing of power fluctuations. In contrast, the geographical distribution of turbines on land means that the aggregation of wind power over a large area leads to a smoothing of the total power generation [9, 3, 2].

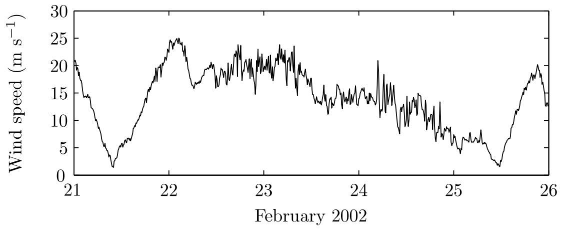

Figure 1: Wind speed observed at a height of 62 m at an offshore measurement mast to the northwest of the Horns Rev I wind farm between 21 and 26 February 2002. The wind speed was measured every 10 minutes.

Some fluctuations in wind speed, such as those on 22 and 23 February 2002 in figure 1, occur when the wind speed is above 15 m s^{-1}, which means that they fall in the constant part of the wind farm power curve and will not be translated to large variations in power. At other times, such as on 24 February in figure 1, the fluctuations fall within the wind speed range of 5–15 m s^{-1}, and will therefore be amplified by the steepest part of the power curve.

Wind power fluctuations have a technical and financial cost. From a financial perspective, unexpected fluctuations in wind speed lead to errors in day-ahead sport market power forecasts, which means that revenue is lost and financial penalties can be applied [5]. As wind energy penetration increases, large fluctuations in produced power could actually have implications for the stable operation of power systems, particularly if the variability is correlated over two or more large offshore wind farms.

Day ahead predictions of the expected occurrence, amplitude and frequency of large hour-scale wind fluctuations can lead to better planning, judicious allocation of reserve power and the possibility of managing the generation of wind power during episodes of extreme fluctuations in order to decrease the amplitude of the swings in power production.

Meteorological phenomena that can lead to hour-scale wind fluctuations over the sea include organised boundary layer structures such as convective rolls, open and closed cellular convection. Such structures have length scales in the order of tens of kilometers, and can therefore cause wind speed variations on time scales in the order of hours as they move past a wind farm. Inspection of visual satellite pictures over the North Sea suggests that open cellular convection, which is characterised by rings of cloudy air with clear centres, is often observed when severe hour-scale wind fluctuations occur. An example of open cellular convection covering the whole North Sea area at 1145 UTC on 5 October 2003 is shown in figure 2.

This paper demonstrates the predictability of hour-scale wind fluctuations at the Horns Rev wind farm from two different perspectives. Firstly, the locally observed wind fluctuations from a measurement mast at the Horns Rev I wind farm are categorised according to the large scale weather patterns. This addresses the predictability of hour-scale wind farms based on large scale weather models which do not, themselves, contain variability on such a small scale. Secondly, cases of observed wind variability at the Horns Rev I wind farm are simulated using the Weather Research and Forecasting model (WRF). It is shown that realistic open cellular convection patterns and explicit hour scale wind fluctuations are reproduced in the simulation.

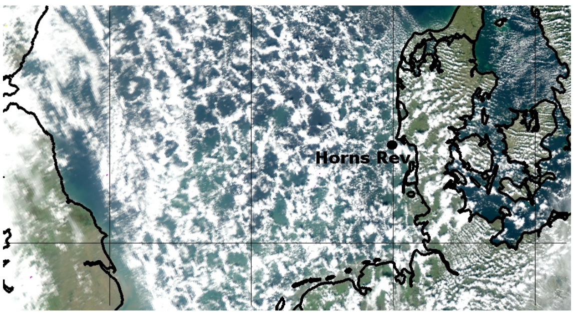

Figure 2: Open cellular convection observed in a visual satellite image over the North Sea, 5 October 2003 1145 UTC. The image is from the TERRA MODIS satellite.

2 Approach

2.1 Severe variability events

To analyse the occurrence and predictability of hour-scale wind fluctuations, an objective metric of 'variability' is required. Such a metric should describe the amplitude of wind fluctuations within a certain range of frequencies, and should respond rapidly to the sudden changes in statistical properties of wind speed time series. Here, the Hilbert-Huang transform [6] was used to calculate the time-evolving spectrum of wind speed time series, as described in [18, 19]. A scalar metric of variability was calculated by integrating the adaptive spectrum between frequencies of 9.3 $\times 10^{-5}$ and 2.8 $\times 10^{-4}$ Hz, corresponding to periods of 1–3 hours. The scalar variability metric for periods of 1–3 hours is shown in figure 3 for the same time series that was shown in figure 1. The metric does not depend on the absolute value of the wind speed, and responds quickly to sudden changes in statistical properties of the wind speed. For the purposes of this work, hour-scale variability refers to the magnitude of the variability metric for periods between 1 and 3 hours.

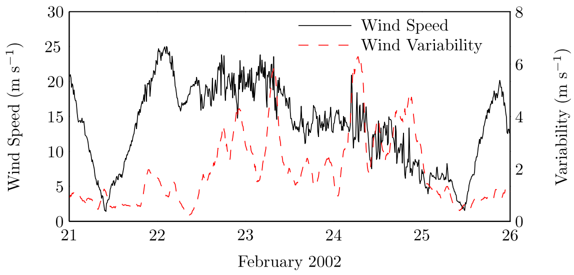

Figure 3: Time series of wind speed observed at Horns Rev 1 between 21 and 26 February 2002 (solid black line) and the corresponding metric of variability (dashed red line) for all periods within the range 1–3 hours (dashed red line).

The exact definition of an episode of wind variability that is considered as 'severe' depends not only on the meteorological conditions, but on the actual impacts that the event has on end-users such as transmission system operators or wind farm operators. For the purpose of this study, we define a 'severe' variability event as a 24 hour period where the average variability is above the 95th percentile for all such 24 hour periods. This means that during the 4 year period 2000–2003, there are 73 extreme variability days.

2.2 Large scale weather classification

To classify the severe variability events according to large scale weather patterns, the self organising maps (SOM) clustering algorithm [8] was used to create a catalogue of weather types for northwest Europe and the northeast Atlantic Ocean. The SOMs algorithm works by iteratively nudging an array of first-guess nodes towards the input data. Benefits of the method include its flexibility and the fact that the topology of the array reflects the topology of the input data in its original, higher dimensional space. SOMs have been used by authors including [4] and [11] for the analysis of large scale weather patterns. In our case, the input data are the daily mean sea level pressure analyses of the ECMWF's ERA interim reanalysis [15] for the 20 year period 1990–2009. For each matrix of MSLP values, the mean pressure over the chosen domain was subtracted, so that the input vectors actually reflected the deviation from the mean pressure in the region, rather than the absolute pressure. A SOMs array of dimensions 6 × 6 was chosen, giving 36 categories of large scale weather. Although there is no objective way of choosing the right number of SOMs, the choice of a 6 × 6 was motivated by the heuristic reasoning of producing categories that were obviously different from one another, and which effectively separated different classes of weather patterns. These arguments are similar to those presented by [4, 14, 10]. The SOMs algorithm was implemented using the R statistical software with the package 'Kohonen' [20].

The 36 large scale weather pattern categories for the SOMs analysis are shown in figure 4. The patterns transition smoothly across the array. The North Sea is dominated by light winds and high pressure in the bottom right of the array, by transitional scenarios between high and low pressure in the centre of the array, and mainly by areas of low pressure at the top of the array. For reference, the SOMs categories are labelled in the bottom left corner of each plot as numbers 1 to 36. The proportion of days in each SOMs category is shown in figure 5, where it is seen that the algorithm does not impose any condition of distributing the input data evenly amongst the categories.

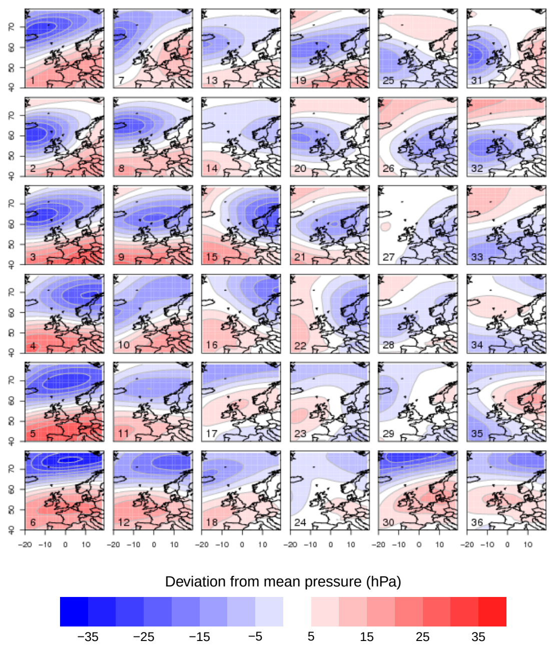

Figure 4: SOMs array of MSLP patterns over northwest Europe and the northeast Atlantic. The array was trained using 20 years of ERA interim reanalysis data.

The 36 SOMs categories were used to classify the 73 severe wind variability events at Horns Rev I during the period 2000–2003. One analysis per day was used, and the 24 hour wind speed records that were used to determine the severe variability days were centered on the analysis time of 00 UTC.

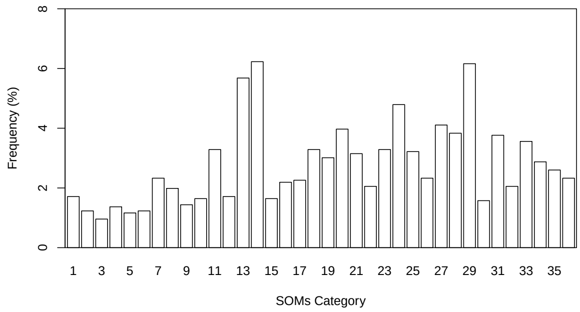

Figure 5: The proportion of days in each SOMs category.

2.3 WRF modelling

The predictability of hour-scale wind fluctuations using a mesoscale model was tested using the Weather Research and Forecasting model version 3.2 with the ARW core [16]. The WRF model was set up with four nests of 54 km, 18 km, 6 km and 2 km respectively, the boundaries and topography of which are shown in figure 6. Initial and boundary conditions were from the GFS-FNL analysis. There were 37 vertical levels, with the lowest five model levels close to 14 m, 53 m, 105 m, 163 m and 228 m. The setup of the WRF model is given in table 1.

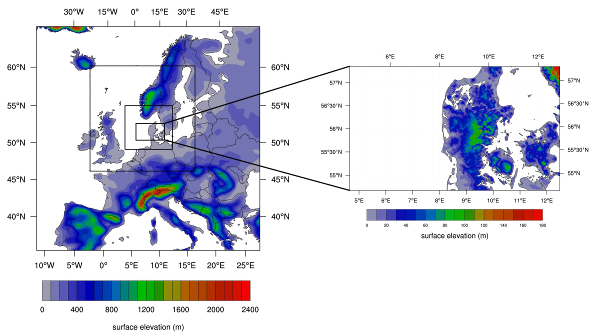

Figure 6: The four nested domains for the WRF simulation. Domain 4 is shown in greater detail, with a finer scale for the surface elevation contours. Note the different colour scale for the two plots.

A set of case studies relating to eight of the extreme variability days that were identified using the Hilbert-Huang variability metric were chosen for analysis. In all cases, open cellular convection was observed over the North Sea. Only one of the cases is chosen for presentation here.

Domain	1	2	3	4
dx	54 km	27 km	6 km	2 km
dt	216 s	108 s	36 s	12 s
Topography resolution	10′	10′	2′	30″
Cumulus parametrisation	K-F	K-F	K-F	None
Vertical levels	37			
Microphysics scheme	Thompson et al scheme			[17]
PBL physics	MYNN scheme			[13]
Long-wave radiation physics	RRTM scheme			[12]
Short-wave radiation physics	Dudhia scheme			[1]
6th order diffusion	On			
Diffusion	Diffusion along coordinate surfaces			

Table 1: Setup of the WRF model that was used in the case study simulations. K-F stands for the Kain-Fritsch cumulus scheme [7]. dx refers to the horizontal grid spacing, and dt refers to the integration time step.

3 Results

The number and proportion of extreme variability days in each SOMs category is shown in figure 7, where the array has the same layout as in figure 4.

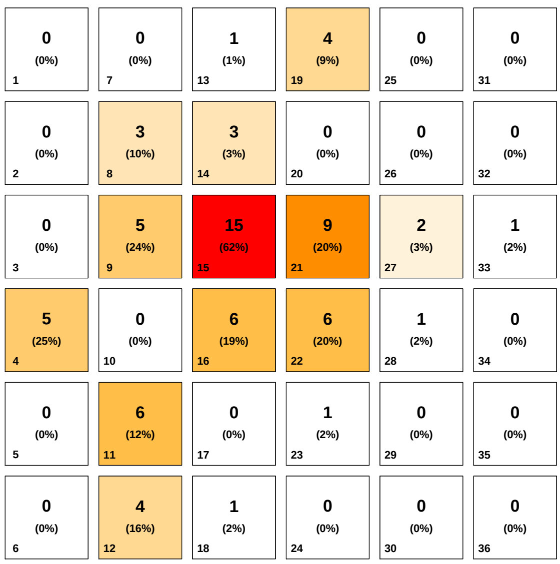

Figure 7: The number of extreme wind variability days at Horns Rev I in each SOMs category during the period 2000–2003. The number of extreme wind variability days as a percentage of the total number of days in each category is indicated in brackets. The layout of the array is the same as in figure 4.

Category 15 stands out as the category with the most extreme variability events, with 15 cases, or 62%. The categories with the highest number of extreme variability days are by no means the most popular categories overall - for example, figure 5 shows that category 15 occurs relatively infrequently. Category 21 has 9 cases (20%), categories 11, 16 and 22 each have 6 cases (12%, 19% and 20% respectively), and category 4 has 5 cases (25%). Altogether, 47 out of the 73 extreme variability days fell within these 5 SOMs categories. There are 19 categories that do not have any extreme variability cases.

Categories 4, 11, 15, 16 and 22 share the common characteristic of westerly to northerly flow over the North Sea. For example, an enlarged version of MSLP contours for category 15 is shown in figure 8, where an arrow indicates the direction of the geostrophic wind over the North Sea. The contours indicate a deep northerly component to the flow, with very cold air originating from the Arctic region. In contrast, category 21 has an area of low pressure over the North Sea itself.

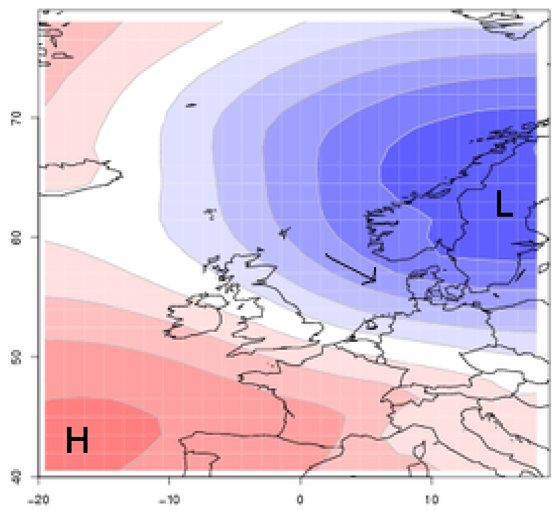

Figure 8: MSLP for SOMs category 15. The high and low pressure areas are labelled with H and L respectively, and the arrow indicates the direction of the geostrophic wind over the North Sea.

Predicting hour-scale wind variability using patterns in the large scale weather is based on the assumption that there are a fairly simply defined set of weather scenarios which uniquely determine the likelihood that the weather phenomena responsible for hour-scale wind fluctuations will develop. A different approach is to explicitly model mesoscale wind fluctuations using a high resolution numerical weather prediction model. Due to the chaotic nature of the atmosphere, hour-scale wind fluctuations are, in general, a stochastic process. Although the model and the observations each give only one realisation of the wind speed time series, small changes in the model or the atmospheric conditions will lead to differences in the precise location and timing of the individual cells. This means that the exact timing of the fluctuations is impossible to predict in a deterministic sense. Therefore, a high resolution numerical weather prediction model is not expected to simulate the phase of the fluctuations, but could reasonably be expected to include realistic information about the existence, amplitude and frequency of the fluctuations.

As described in the approach section, the mesoscale model was run with four nests, the smallest (domain 4) having a horizontal grid spacing of 2 km. Vertical velocity for the second model level (53 m) is shown in figure 9 for hour 24 of a simulation initialised on 4 October 2003 12 UTC, which means that it is valid for 5 October 2003 12 UTC. 4 October and 5 October fall in SOMs categories 15 and 16 respectively, so the case is representative of favourable large scale weather patterns for severe wind variability. The case also corresponds to the satellite picture in figure 2. After the first couple of hours of the simulation, cellular structures developed. It can be seen that the length scales of the cellular patterns in figure 9 are similar to those in the satellite picture. The cellular patterns did not generally cover the whole North Sea area in the way that they did in the satellite picture. Instead they tended to form and decay in different parts of the domain at different times. This could be partly due to limitations imposed by the domain size.

Time series of model values for the point closest to the M2 meteorological mast at Horns Rev I were saved for the third model level. The model output, which was stored at every 12 s time step, was averaged to match the 10 minute time step of the observations. The simulation started 12 hours before the 24 hour period of interest, and ran for 36 hours to cover the whole case. This means the first few hours of the simulation, which are initialised from the coarse resolution initial conditions, can be disregarded. The full 36 hour forecast at a height of 53 m and observed time series at a height of 62 m are shown in figure 10. Large wind fluctuations are apparent in both the observed and modelled time series. The large wind fluctuations around hour 12 of the simulation correspond to the plot of vertical velocity in figure 9.

To diagnose the variability in the forecast and observed time series in a simple way, the variance was calculated over a three hour moving window for both the observed and the modelled time series. The Hilbert-Huang transform, which was used to diagnose variability over precise frequency bands in long climatic time series was not used here due to the challenges of dealing with the end effects on such short time series. The variance does not reflect the frequencies at which the fluctuations occur, and it therefore responds strongly to a single large change in wind speed as well as to extended periods of smaller fluctuations. The three hour moving variance is shown as dotted lines in figure 10.

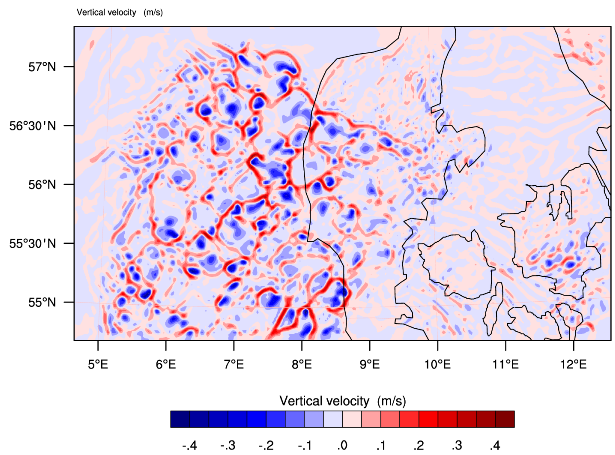

Figure 9: Vertical velocity for the third model level for domain 4. Simulation hour 24 for a simulation initialised 4 Oct 2003 12UTC.

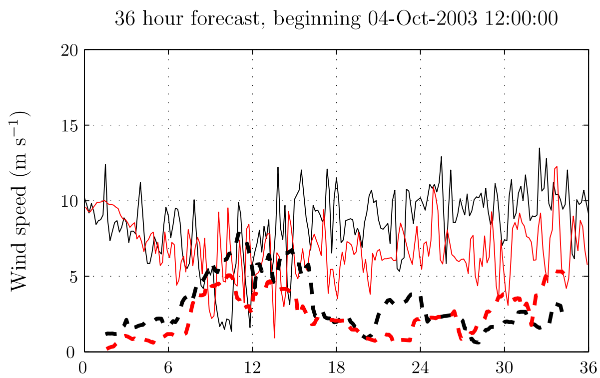

Figure 10: Simulated and observed time series of wind speed at Horns Rev I for the simulation initialised on 4 October 2003 12 UTC. Black - Observations at a height of 62 m. Red - Model simulation at a height of 53 m. Solid lines - wind speed. Dashed lines - three hour moving variance.

4 Discussion and Conclusions

In this work, two approaches to the modelling and prediction of hour-scale wind variability were presented.

Firstly, hour-scale wind variability observed over a 4 year period at the Horns Rev I wind farm was related to large scale weather patterns. It was shown that hour-scale wind fluctuations are much more likely to occur in certain weather types, mostly relating to flow over the North Sea with a deep northerly component. The implications of these results are that it could be possible to predict hour-scale wind variability without resorting to computationally demanding high resolution modelling.

Secondly, the possibility of explicitly predicting hour-scale wind fluctuations using a high resolution numerical weather prediction model was explored. In the case study presented here, the WRF mesoscale model run with a horizontal grid spacing of 2 km was able to reproduce realistic, but out-of-phase, fluctuations in the horizontal wind speed. Although only one case was presented here, similar results were obtained for a set of eight case studies. These results show that there are good possibilities for the practical use of high resolution numerical weather models for providing day ahead predictions of the onset of hour-scale wind fluctuations. The results apply not only to mesoscale models, where the vertical mixing is parameterised through the planetary boundary layer scheme, but to even high resolution large eddy simulation models which could one day be applied to practical applications in weather forecasting.

This work focused on fluctuations in the wind speed itself, but for wind power applications it is fluctuations in the produced power that are of practical significance. There are several reasons why it is easier to focus on wind speed fluctuations. The non-linear nature of the power curve means that a similar meteorological event occurring with a background mean speed of around 7 m s^{-1} will have a totally different impact on the produced power compared to an event occurring with a background mean wind speed of 16 m s^{-1}. Furthermore, fluctuations in the power produced by individual turbines will be somewhat smoothed by out-of-phase neighbouring turbines. This effect, which becomes very significant when considering an extensive geographical area containing many large wind farms, is an interesting area for further study, since it requires an understanding of the spatial correlation structures in wind fluctuations.

Only the variability conditions at the Horns Rev wind farm have been explored here. It is likely that at different sites, there will be different sets of weather conditions that contribute to the hour-scale wind variability. For example, on land, topographic effects and convection initiated by diurnal heating will play a more important role than they do for offshore sites, while open cellular convection is not usually observed over the land.

Both methods suggest that there is the possibility for producing practical forecasts of day-ahead wind variability, but in neither case do we expect to be able to predict the phase of the fluctuations. That is, it may be possible to provide day-ahead information about the expected occurrence, amplitude and frequency of large wind fluctuations, but not timing of each peak or trough in wind speed. Obtaining useful information from day-ahead variability forecasts will benefit from a shift from deterministic to stochastic forecasting and power management.

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